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	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

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14. ABSTRACT

The focus of our effort has been to develop quantum information processing technologies based on a solid-state cavity QED platform consisting of quantum dots in photonic crystals. The main goals that we have accomplished include:
1. Study of the ultrafast dynamics of the quantum dot-cavity QED system [Majumdar et al., Phys. Rev. A, 2012], and ultrafast switching between two single photon pulses mediated by the quantum dot-photonic crystal cavity

15. SUBJECT TERMS

Quantum information processing, quantum repeater,quantum gates , quantum dot, photonic crystal, cavity QED

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Jelena Vuckovic
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Report Title

Quantum dot-photonic crystal cavity QED based
quantum information processing

ABSTRACT

The focus of our effort has been to develop quantum information processing technologies based on a solid-state cavity QED platform consisting of quantum dots in photonic crystals. The main goals that we have accomplished include:

1. Study of the ultrafast dynamics of the quantum dot-cavity QED system [Majumdar et al., Phys. Rev. A, 2012], and ultrafast switching between two single photon pulses mediated by the quantum dot-photonic crystal cavity QED system [Englund et al., Phys. Rev. Letters, 2012]
2. Probing the ladder of dressed states in the solid state cavity QED system [Majumdar et al, Physical Review A, 2012]
3. Study of the off-resonant quantum dot-cavity coupling in solid-state cavity QED system, and the phonon mediated off-resonant interaction between two quantum dots [Majumdar et al., Physical Review B , 2012]
4. Coherent optical spectroscopy of a single quantum dot via an off-Resonant cavity - much simpler than in conventional approaches [Majumdar et al, Physical Review B, 2011; Papageorge et al., New. Journal of Physics, 2011]
5. Study of the cavity QED with a quantum dot coupled to a photonic molecule [Majumdar et al., Phys. Rev. B, 2012]
6. Study of the effect of photo-generated carriers on the spectral diffusion of a quantum dot coupled to a photonic crystal cavity [Majumdar et al., Physical Review B, 2011]

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/08/14 1	18	Erik D. Kim, Yiyang Gong, Michal Bajcsy, Jelena Vuckovic, Arka Majumdar. Phonon mediated off-resonant quantum dot–cavity coupling under resonant excitation of the quantum dot, Physical Review B, (08 2011): 85309. doi: 10.1103/PhysRevB.84.085309
2012/08/14 1	19	Arka Majumdar, Alexander Papageorge, Erik Kim, Michal Bajcsy, Hyochul Kim, Pierre Petroff, Jelena Vuckovic. Probing of single quantum dot dressed states via an off-resonant cavity, Physical Review B, (08 2011): 85310. doi: 10.1103/PhysRevB.84.085310
2012/08/14 1	21	Armand Rundquist, Arka Majumdar, Jelena Vuckovic. Off-resonant coupling between a single quantum dot and a nanobeam photonic crystal cavity, Applied Physics Letters, (12 2011): 251907. doi: 10.1063/1.3671458
2012/08/14 1	20	Arka Majumdar, Erik Kim, Jelena Vuckovic. Effect of photogenerated carriers on the spectral diffusion of a quantum dot coupled to a photonic crystal cavity, Physical Review B, (11 2011): 195304. doi: 10.1103/PhysRevB.84.195304
2012/08/14 1	24	Arka Majumdar, Dirk Englund, Michal Bajcsy, Jelena Vuckovic. Nonlinear temporal dynamics of a strongly coupled quantum-dot–cavity system, Physical Review A, (03 2012): 33802. doi: 10.1103/PhysRevA.85.033802
2012/08/14 1	26	Arka Majumdar, Michal Bajcsy, Armand Rundquist, Erik Kim, Jelena Vuckovic. Phonon-mediated coupling between quantum dots through an off-resonant microcavity, Physical Review B, (05 2012): 195301. doi: 10.1103/PhysRevB.85.195301
2012/08/14 1	28	Arka Majumdar, Armand Rundquist, Michal Bajcsy, Jelena Vuckovic. Cavity quantum electrodynamics with a single quantum dot coupled to a photonic molecule, Physical Review B, (07 2012): 45315. doi: 10.1103/PhysRevB.86.045315
2012/08/14 1	29	Arka Majumdar, Dirk Englund, Erik Kim, Michal Bajcsy, Jelena Vuckovic, Andrei Faraon. Integrated quantum optical networks based on quantum dots and photonic crystals, New Journal of Physics, (05 2011): 55025. doi: 10.1088/1367-2630/13/5/055025
2012/08/14 1	27	Arka Majumdar, Michal Bajcsy, Armand Rundquist, Jelena Vuckovic. Loss-Enabled Sub-Poissonian Light Generation in a Bimodal Nanocavity, Physical Review Letters, (05 2012): 183601. doi: 10.1103/PhysRevLett.108.183601
2012/08/14 1	25	Arka Majumdar, Michal Bajcsy, Jelena Vuckovic. Probing the ladder of dressed states and nonclassical light generation in quantum-dot–cavity QED, Physical Review A, (04 2012): 41801. doi: 10.1103/PhysRevA.85.041801
2012/08/14 1	23	Arka Majumdar, Michal Bajcsy, Andrei Faraon, Pierre Petroff, Jelena Vuckovic, Dirk Englund. Ultrafast Photon-Photon Interaction in a Strongly Coupled Quantum Dot-Cavity System, Physical Review Letters, (03 2012): 93604. doi: 10.1103/PhysRevLett.108.093604
2012/08/14 1	22	Alexander Papageorge, Arka Majumdar, Erik D Kim, Jelena Vuckovic. Bichromatic driving of a solid-state cavity quantum electrodynamics system, New Journal of Physics, (01 2012): 0. doi: 10.1088/1367-2630/14/1/013028
2012/08/14 1	30	Kelley Rivoire, Sonia Buckley, Arka Majumdar, Hyochul Kim, Pierre Petroff, Jelena Vuc?kovic?. Fast quantum dot single photon source triggered at telecommunications wavelength, Applied Physics Letters, (02 2011): 83105. doi: 10.1063/1.3556644
2010/08/31 1	17	A. Majumdar, A. Faraon, E. Kim, D. Englund, H. Kim, P. Petroff, J. Vuckovic. Linewidth broadening of a quantum dot coupled to an off-resonant cavity, Physical Review B, (07 2010): . doi:
2010/08/31 1	16	A. Majumdar, Z. Lin, A. Faraon, J. Vuckovic. Proposal for high-speed and high-fidelity electron-spin initialization in a negatively charged quantum dot coupled to a microcavity in a weak external magnetic field, Physical Review A, (08 2010): . doi:
2010/08/31 1	15	E. Kim, A. Majumdar, H. Kim, P. Petroff, J. Vuckovic. Differential Reflection Spectroscopy of a Single Quantum Dot Strongly Coupled to a Photonic Crystal Cavity, Applied Physics Letters, (08 2010): . doi:

2010/08/31 0!	14	A. Majumdar, N. Manquest, A. Faraon, J. Vuckovic. Theory of Electro-Optic Modulation Via a Quantum Dot Coupled to a Nano-Resonator, Optics Express, (03 2010): . doi:
2010/08/31 0!	13	D. Englund, A. Majumdar, A. Faraon, M. Toishi, N. Stolz, P. Petroff, J. Vuckovic. Resonant Excitation of a Quantum Dot Strongly Coupled to a Photonic Crystal Nanocavity, Physical Review Letters, (02 2010): . doi:
2010/08/30 1!	12	A. Faraon, A. Majumdar, H. Kim, P. Petroff, J. Vuckovic. Fast Electrical Control of a Quantum Dot Strongly Coupled to a Photonic-Crystal Cavity, Physics Letters, (01 2010): . doi:
2010/08/30 1!	11	Z. Lin, J. Vuckovic. Enhanced two-photon processes in single quantum dots inside photonic crystal nanocavities, Physical Review B, (01 2010): . doi:
2010/08/30 1!	10	J. O'Brien, A. Furusawa, J. Vuckovic. Photonic Quantum Technologies, Nature Photonics, (12 2009): . doi:
2010/08/30 1!	9	D. Englund, A. Faraon, Arka Majumdar, Nick Stoltz, Pierre Petroff, Jelena Vuckovic. An Optical Modulator Based on a Single Strongly Coupled Quantum Dot-Cavity System in a p-i-n Junction", Optics Express, (10 2009): . doi:
2009/08/19 1:	7	A. Faraon, J. Vuckovic. Local temperature control of photonic crystal devices via micron-scale electrical heaters, Applied Physics Letters, (2009): . doi:
2009/08/19 1	6	M. Toishi, D. Englund, A. Faraon, J. Vuckovic. High-brightness single photon source from a quantum dot in a directional-emission nanocavity, Optics Express, (2009): . doi:

TOTAL: 24

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2010/08/30 1!	8	D. Englund, B. Shields, K. Rivoire, F. Hatami, J. Vuckovic, H. Park, M. Lukin. Deterministic Coupling of a Single Nitrogen Vacancy Center to a Photonic Crystal Cavity, (05 2010)
2009/08/19 1(	5	D. Englund, A. Faraon, A. Majumdar, N. Stoltz, P. Petroff, J. Vuckovic. An optical modulator based on a single strongly coupled quantum dot-cavity system in a p-i-n junction, ( )
2009/08/19 1(	4	A. Faraon, A. Majumdar, P. Petroff, J. Vuckovic. Fast Electrical Control of a Quantum Dot Strongly Coupled to a Nano-resonator, ( )
2009/08/19 1(	3	A. Majumdar, Z. Lin, A. Faraon, J. Vuckovic. Fast, High Fidelity Quantum Dot Spin Initialization without a Strong Magnetic Field by Two-Photon Processes, ( )
2009/08/19 1(	2	D. Englund, A. Majumdar, A. Faraon, M. Toishi, N. Stoltz, P. Petroff, J. Vuckovic. Resonant excitation of a quantum dot strongly coupled to a photonic crystal nanocavity, ( )
2009/08/19 0!	1	Z. Lin, J. Vuckovic. Enhanced Two-Photon Processes in Quantum Dots inside Photonic CrystalNanocavities and Quantum Information Science Applications, ( )

TOTAL: 6

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

please see under inventions:
~~A. Faraon, I. Fushman, D. Englund, and J. Vuckovic, “Optical Cavity Emitter Arrangements With Spectrally-Aligned~~
Quantum Dots And Methods Therefor,” Stanford disclosure S07-078 (US patent approved, May 5, 2011, Serial Number 12/134,414)

Patents Awarded

please see under inventions:
~~A. Faraon, I. Fushman, D. Englund, and J. Vuckovic, “Optical Cavity Emitter Arrangements With Spectrally-Aligned~~
Quantum Dots And Methods Therefor,” Stanford disclosure S07-078 (US patent approved, May 5, 2011, Serial Number 12/134,414)

Awards

Jelena Vuckovic, Humboldt Prize, 2010

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Arka Majumdar	0.20	
Pranjal Bordia	0.06	
Armand Rundquist	0.06	
Nicolas Manquest	0.06	
Andrei Faraon	0.06	
Ziliang LIn	0.03	
FTE Equivalent:	**0.47**	
Total Number:	**6**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Michal Bajcsy	0.10
Erik Kim	0.00
FTE Equivalent:	**0.10**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jelena Vuckovic	0.15	
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME	
Nicolas Manquest	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Arka Majumdar	
Andrei Faraon	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

please see the attached pdf file

Technology Transfer

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Note: 15 pages total

Publications (since the previous interim report)

Published in Peer-Reviewed Journals

1. **Phonon mediated off-resonant quantum dot-cavity coupling under resonant excitation of the quantum dot**, Arka Majumdar, Erik D. Kim, Yiyang Gong, Michal Bajcsy, and Jelena Vuckovic, *Physical Review B* 84, 085309 (2011)
2. **Probing of single quantum dot dressed states via an off-resonant cavity**, Arka Majumdar, Alexander Papageorge, Erik D. Kim, Michal Bajcsy, Hyochul Kim, Pierre Petrof, and Jelena Vuckovic, *Physical Review B* 84, 085310 (2011)
3. **The effect of photo-generated carriers on the spectral diffusion of a quantum dot coupled to a photonic crystal cavity**, Arka Majumdar, Erik D. Kim, and Jelena Vuckovic, *Physical Review B* 84, 195304 (2011)
4. **Off-resonant coupling between a single quantum dot and a nanobeam photonic crystal cavity**, Armand Rundquist, Arka Majumdar, and Jelena Vuckovic, *Applied Physics Letters* 99, 251907 (2011)
5. **Bichromatic driving of a solid-state cavity quantum electrodynamics system**, Alexander Papageorge, Arka Majumdar, Erik D Kim and Jelena Vuckovic, *New Journal of Physics* 14, 013028 (2012)
6. **Ultrafast Photon-Photon Interaction in a Strongly Coupled Quantum Dot-Cavity System**, Dirk Englund, Arka Majumdar, Michal Bajcsy, Andrei Faraon, Pierre Petroff, and Jelena Vuckovic, *Physical Review Letters* 108, 093604 (2012)
7. **Nonlinear Temporal Dynamics of Strongly Coupled Quantum Dot-Cavity System**, Arka Majumdar, Dirk Englund, Michal Bajcsy, and Jelena Vuckovic, *Physical Review A* 85, 033802 (2012)
8. **Probing the ladder of dressed states and nonclassical light generation in quantum-dot-cavity QED**, Arka Majumdar, Michal Bajcsy, Jelena Vuckovic, *Physical Review A* 85, 041801 (2012)
9. **Phonon-mediated coupling between quantum dots through an off-resonant microcavity**, Arka Majumdar, Michal Bajcsy, Armand Rundquist, Erik Kim, and Jelena Vuckovic, *Physical Review B* 85, 195301 (2012)
10. **Loss-enabled sub-Poissonian light generation in a bimodal nanocavity**, Arka Majumdar, Michal Bajcsy, Armand Rundquist, and Jelena Vuckovic, *Physical Review Letters* 108, 183601 (2012)

11. **[Cavity Quantum Electrodynamics with a Single Quantum Dot Coupled to a Photonic Molecule]**, Arka Majumdar, Armand Rundquist, Michal Bajcsy, and Jelena Vuckovic, *Physical Review B, vol.* 86, 045315 (2012)

Published in non-peer reviewed journals

N/A

Papers presented at meetings, but not published in conference proceedings

1. Jelena Vuckovic, *2012 Karles Invitational Quantum Information Science and Technology Conference*, Naval Research Laboratory, Washinton DC, Aug 27-28, 2012
2. Jelena Vuckovic, "Nonlinear optics at the single photon level in optical nanocavities," *Optics and Quantum Electronics Seminar, Ginzton Lab,* Stanford University, Nov. 2011
3. Jelena Vuckovic, " Quantum dots in optical nanocavities: from cavity QED to device applications," *MIT Physics Colloquium*, Nov. 2011

Non-peer reviewed conference publications

Invited talks at major international conferences

4. Jelena Vuckovic, “Cavity QED and quantum optics with a single quantum dot in a photonic crystal cavity or a photonic molecule,” *23rd International Conference on Atomic Physics (ICAP 2012),* session on "Quantum optics and cavity QED," Ecole Polytechnique, Palaiseau, Paris, July 23-27, 2012
5. Jelena Vuckovic, Arka Majumdar, Michal Bajcsy, Armand Rundquist, Dirk Englund, Andrei Faraon, “Strong photon-photon and photon – phonon interaction in a coupled quantum dot-photonic crystal nanocavity,” *PECS-X*, Santa Fe, New Mexico, June 3–8, 2012
6. Jelena Vuckovic, "Quantum dots in optical nanocavities: from cavity QED to device applications," *7th International Conference on Quantum Dots (QD 2012)*, Santa Fe, New Mexico, USA, May 14 -18, 2012
7. Jelena Vuckovic, “Quantum dot - nanocavity QED for quantum information processing,” Focus session on "Semiconductor-based quantum communication" *Spring meeting of the German Physical Society*, Berlin, Germany, March 2012
8. Jelena Vuckovic, " Strong photon-photon interaction in a coupled quantum dot- photonic crystal nanocavity," *APS March Meeting*, session on “Strongly interacting photons,” Boston, MA, Feb-March 2012
9. Jelena Vuckovic, Arka Majumdar, Alexander Papageorge, Armand Rundquist, Yiyang Gong, Erik Kim, and Michal Bajcsy, "Opto-mechanics and quantum dot-nanocavity QED," *Frontiers in Optics,* San Jose, CA, 16-20 October 2011.

Peer-reviewed conference publications

1. “Phonon Mediated Off-resonant Quantum Dot-Cavity Coupling,” Arka Majumdar, Armand Rundquist, Michal Bajcsy, Alexander Papageorge, Erik D. Kim, Jelena Vuckovic, *7th International Conference on Quantum Dots (QD 2012),* Santa Fe, NM (May 2012)
2. "Off-resonant Coupling Between a Single Quantum Dot and a Nanobeam Photonic Crystal Cavity," Armand Rundquist, Arka Majumdar, and Jelena Vuckovic, *CLEO*, San Jose, CA, May 2012
3. "Ultrafast Nonlinear Dynamics in Strongly Coupled Quantum Dot-Cavity system," Arka Majumdar, Dirk Englund, Michal Bajcsy, and Jelena Vuckovic, *CLEO*, San Jose, CA, May 2012
4. "Phonon Mediated off-resonant Quantum Dot-Cavity Interaction," Arka Majumdar, Erik D. Kim, Michal Bajcsy, Armand Rundquist, and Jelena Vuckovic, *APS March Meeting*, Boston, MA, March 2012
5. "Multi-photon State Generation from Strongly Coupled Quantum Dot-Cavity System," Michal Bajcsy, Arka Majumdar, and Jelena Vuckovic, *Frontiers in Optics*, San Jose, CA, Oct. 2011
6. "Quantum Dot Dressing Observed via Off-resonant Cavity," Arka Majumdar, Alexander Papageorge, Erik Kim, Michal Bajcsy, Jelena Vuckovic, *Frontiers in Optics and Laser Science*, San Jose, CA (Oct. 2011)

Books

N/A

Honors and Awards

N/A

Patents

N/A

Scientific Personnel Supported by This Project

Senior Researchers
Jelena Vuckovic (15% of one quarter)

Postdoctoral Scholars
1. Michal Bajcsy
2. Erik Kim (supported by the IC postdoctoral fellowship)

Graduate Students
1. Arka Majumdar (supported by the Stanford Graduate Fellowship)
2. Pranjal Bordia (graduate rotation student, supported for one quarter)
3. Armand Rundquist (supported by the Stanford Graduate Fellowship)

MSc Degrees Awarded

N/A

Undergraduate Students

N/A

PhD Degrees

Arka Majumdar, oral defense of PhD thesis in June 2012 (written PhD thesis to be submitted by Sept. 2012)

Scientific progress and accomplishments

Abstract:

The focus of our effort has been to develop quantum information processing technologies based on a solid-state cavity QED platform consisting of quantum dots in photonic crystals. The main goals that we have accomplished include:

1. Study of the ultrafast dynamics of the quantum dot-cavity QED system [Majumdar *et al.*, *Phys. Rev. A*, 2012], and ultrafast switching between two single photon pulses mediated by the quantum dot-photonic crystal cavity QED system [Englund *et al.*, *Phys. Rev. Letters*, 2012]
2. Probing the ladder of dressed states in the solid state cavity QED system [Majumdar et al, *Physical Review A*, 2012]
3. Study of the off-resonant quantum dot-cavity coupling in solid-state cavity QED system, and the phonon mediated off-resonant interaction between two quantum dots [Majumdar *et al.*, *Physical Review B* , 2012]
4. Coherent optical spectroscopy of a single quantum dot via an off-Resonant cavity - much simpler than in conventional approaches [Majumdar et al, *Physical Review B,* 2011*; Papageorge et al., New. Journal of Physics,* 2011] – described in the previous interim report
5. Study of the cavity QED with a quantum dot coupled to a photonic molecule [Majumdar *et al.*, *Phys. Rev. B,* 2012]
6. Study of the effect of photo-generated carriers on the spectral diffusion of a quantum dot coupled to a photonic crystal cavity [Majumdar *et al.*, *Physical Review B*, 2011]

The platform we use in our experiments consists of InAs quantum dots (QDs) embedded in GaAs photonic crystal (PC) circuits. The QD material is grown by our collaborators at UCSB (Pierre Petroff) and PCs are fabricated by our group in the Stanford Nanofabrication Facility (SNF).

The detailed descriptions of these achievements follow.

1. Ultrafast dynamics of the QD-cavity QED system

We have performed theoretical and experimental studies of the ultrafast dynamics of the quantum dot –photonic crystal cavity system [1]. We derived simplified linear and nonlinear semi-classical models that approximate well the system's behavior in the limits of high- and low-power driving pulses and describe the role of quantum coherence in the exact dynamics of the system. We also present time-resolved transmission measurements showing the dynamics of a quantum-dot–cavity system in the presence of a short laser pulse.

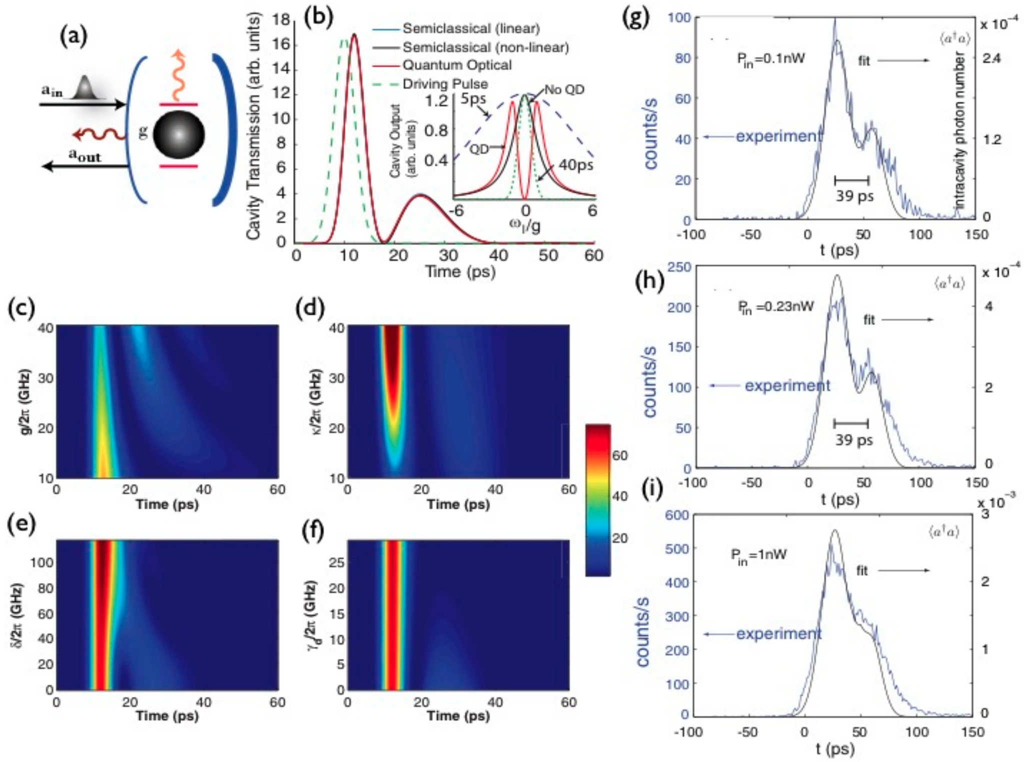

Fig. 1.1 (a) Schematic of the coupled QD- cavity system. It is driven by a laser pulse, and the cavity output is monitored. (b) The cavity transmission calculated by three different models: the quantum optical (red), semiclassical linear (blue) and nonlinear (black) model at low peak intensity of the driving pulse. All three models match quite well. The input pulse is also shown (green dashed line). The oscillation in the cavity output is due to Rabi oscillation of the photon between the QD and the cavity. The inset shows the cavity transmission spectrum in the presence and in the absence of the strongly coupled QD. The split resonances are separated approximately by twice the coherent dot-cavity interaction strength g. The spectral shape of laser pulses with pulse lengths of 5 ps (blue dashed line) and 40 ps (green dashed line) is also shown. The temporal cavity output obtained from the full quantum optical simulation as a function of (c) the dot-cavity coupling strength g, (d) the cavity field decay rate κ, (e) the dot cavity detuning δ, and (f) the pure QD dephasing rate γ_d. (g–i) Experimentally measured time-resolved transmission of 40-ps pulses through a strongly coupled dot-cavity system for three different powers (averaged over the pulse repetition period).

As described in the previous report, this ultrafast dynamics has been employed to demonstrate ultrafast all-optical switching at the single photon level, as shown in the Fig. 1.2

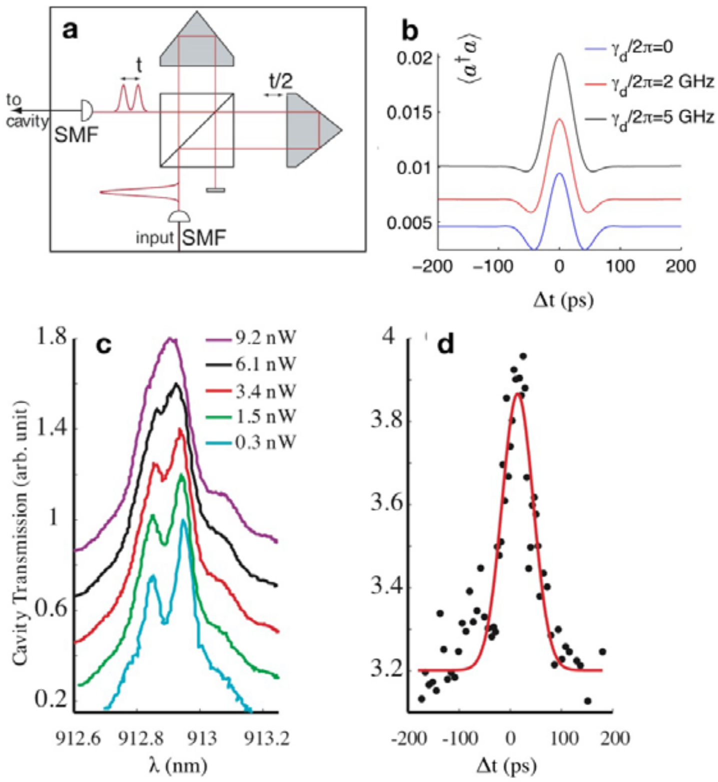

Figure 1.2 Interaction of two weak laser pulses through the QD/cavity system. (a) Time-delay setup for producing pulses at a separation of Δt. (b) Simulated interaction of two laser pulses, represented by the instantaneous intracavity photon number $\langle a^\dagger a \rangle$ as a function of the time delay Δt between the two 40 ps long Gaussian pulses. Curves are calculated for a set of different rates of pure QD dephasing, γ_d, which causes a reduction of the transmission dips before and after the peak. Pure dephasing also causes a blurring of the spectral normal mode splitting, which in turn raises the transmission for increasing γ_d. (c) Pump-power dependence of the cavity transmission for coincident pulses repeating at 80 MHz. (d) Signal observed when the cavity-QD system is probed with two 40 ps pulses as a function of their delay. When the two pulses have a temporal overlap inside the cavity, the QD saturates and the overall cavity reflection increases. The power in the single of the two pulses corresponds roughly to the 3.4nW trace in (c). Best agreement is found with the theoretical plot for a pure dephasing rate $\gamma_d/2\pi \sim 5$ GHz.

2. Probing the ladder of dressed states in the solid state cavity QED system

We have probed the 2nd manifold of the ladder of dressed states of the strongly coupled QD-cavity system [2]. Our investigation focused on the photon-induced tunneling phenomena in a photonic crystal cavity containing a strongly coupled quantum dot. We also theoretically explored how this tunneling can be used to generate photon states consisting mainly of a particular Fock state.

When a cavity mode is strongly coupled to a two-level quantum emitter such as a quantum dot (QD) (Fig 2.1a), the energy structure of the coupled system becomes anharmonic (Fig. 2.1b). Nonclassical correlations between photons transmitted through the cavity can result from such anharmonicity, which in turn leads to fundamental phenomena of photon blockade and photon-induced tunneling [3].

Signatures of the photon blockade and tunneling can be detected through photon-statistics measurements, such as the second-order coherence function at time delay zero $g^{(2)}(0) = \langle a^\dagger a^\dagger aa\rangle/\langle a^\dagger a\rangle^2$. $g^{(2)}(0)$ is less (greater) than 1 in the photon blockade (tunneling) regime, signifying the presence of single (multiple) photons in the light coming out of the coupled QD cavity system. $g^{(2)}(0)$ can be experimentally measured by the Hanbury-Brown and Twiss (HBT) setup, where coincidences between the photons are detected [3]. Another important statistical quantity is the n^{th} order differential correlation function $C^{(n)}(0) = \langle a^{\dagger n}a^n\rangle - \langle a^\dagger a\rangle^n$, which provides a clearer measure of the probability to create n photons at once in the cavity [4]. The second-order differential correlation function can also be expressed as $C^{(2)}(0) = [g^{(2)}(0) - 1]n_c^2$, where $n_c= \langle a^\dagger a\rangle$ is the average intracavity photon number. Particularly for a weakly driven system ($n_c \ll 1$), $C^{(2)}(0)$ becomes positive only when the probability of the two-photon state becomes significant compared to that of a single-photon state, while a peak in $C^{(2)}(0)$ indicates the maximum probability of a two-photon state inside the cavity. As the driving power increases, the peak in $C^{(2)}(0)$ shifts toward empty cavity resonance as one starts populating the higher-order manifolds.

We obtain the values of the second-order differential correlation function $C^{(2)}(0)$ for the coupled-QD cavity system as a function of the laser-cavity detuning by multiplying the second-order coherence function by the normalized value of the system's transmission at a given detuning (Fig 2.1c) . We observe the transition of $C^{(2)}(0)$ from negative to positive values. Simulations with our system parameters are shown by the dashed line in Fig. 2.1c and the onset of a peak at $\Delta_c \sim 0.5g$, corresponding to the excitation of the higher-order dressed states, is observed. The absence of such a clear peak in the experimental data can be ascribed to QD blinking. The peak in $C^{(2)}(0)$ does not correspond exactly to the resonant excitation of the second-order manifold via the two-photon process because of the additional excitation of the higher-order manifolds.

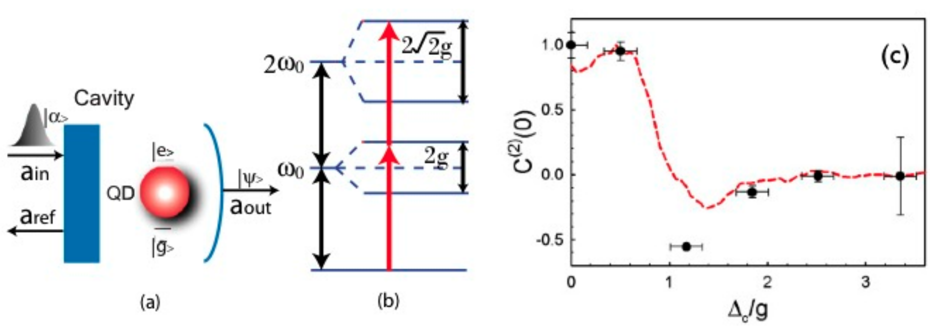

Fig 2.1: (a) Schematic of the coupled QD-cavity system driven by a Gaussian pulse (coherent state $|\alpha\rangle$). The transmitted light through the cavity is nonclassical ($|\psi\rangle$) due to the nonlinearity provided by the strongly coupled QD-cavity system. (b) The anharmonic Jaynes-Cummings ladder structure. (c) Normalized differential correlation function $C^{(2)}(0)$ as a function of the laser detuning. The dashed red line shows the result of a numerical simulation based on the system's experimental parameters.

3. Phonon mediated off-resonant interaction between two quantum dots in a cavity

We have demonstrated phonon-mediated coupling between two quantum dots embedded inside a photonic-crystal microcavity, for both weak and strong regimes of dot-cavity coupling. Phonon-mediated coupling between a self-assembled semiconductor quantum dot (QD) and a semiconductor microcavity is a recently discovered phenomenon unique to solid-state cavity quantum electrodynamics (cQED). This phenomenon has been observed both in photoluminescence studies under above-band pumping [5–9] and under resonant excitation of the QD [10,11]. To isolate the role of phonons in off-resonant QD-cavity coupling, studies employing resonant excitation of the QD are preferable as they avoid possible complications arising from multiexcitonic complexes and nearby charges generated via above-band pumping [12,13].

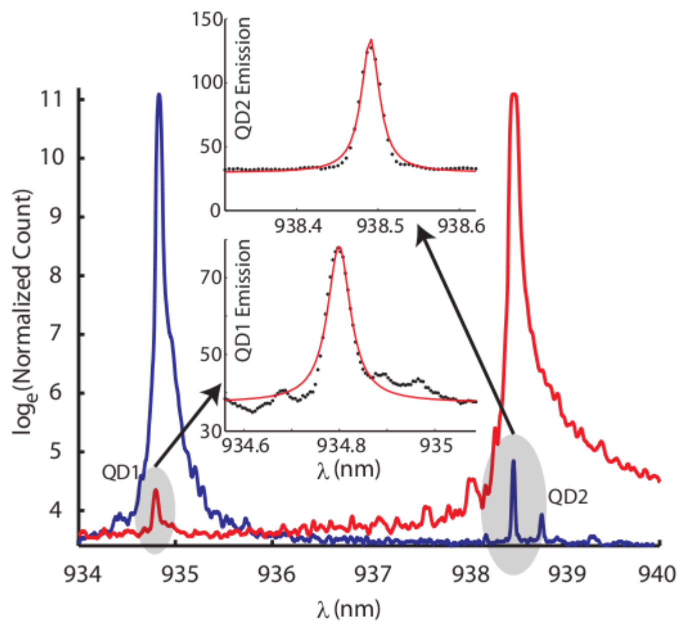

Figure 3.1 Experimental demonstration of the phonon-mediated inter-dot coupling. We observe the emission from the lower-energy QD1 when the higher-energy QD2 is resonantly excited (blue). Similarly, under resonant excitation of the lower energy QD1, emission from the higher-energy QD2 is observed (red). Natural log of the count from the spectrometer CCD is plotted. The inset zooms into the QD emission (the actual spectrometer CCD counts are plotted). QD linewidths are estimated by fitting Lorentzians. Measured linewidths of the higher- and lower-energy QDs, respectively, are ~0.03 nm and ~0.013 nm. The cavity is at ~935 nm, close to the higher-energy QD2.

However, all phonon-assisted off-resonant interaction experiments reported previously in the literature were based on a single QD and a cavity. Recently, an experimental study of two spatially separated QDs interacting resonantly in a microcavity has been reported [14] as well as a theoretical analysis [15–19] of the possible energy-transfer mechanisms between QDs in such a cavity. The interaction between two spectrally detuned QDs via a photonic-crystal cavity has also been demonstrated recently under p-shell QD excitation [20]. However, the actual coupling mechanism between two QDs was not conclusively proven in that experiment as the presence of a higher-energy pumping laser can create charges and multiexcitons, making the system more complex.

In our work, we show that under resonant excitation (of one of the dots), two spectrally far-detuned QDs can interact with each other via an off-resonant cavity. More specifically, we observe emission from a spectrally detuned QD when another QD is resonantly excited (as shown in Fig. 3.1). Both frequency down-conversion (energy transfer from a higher-energy QD to a lower-energy QD) and up-conversion (energy transfer from a lower-energy QD to a higher-energy QD) are observed for a frequency separation of up to $\sim\pm 1.2$ THz. Such a large energy difference cannot be ascribed to an excited state of the same QD as opposed to conclusions reached in an earlier work by Flagg et al. [21], which was performed without a cavity and for a frequency difference of $\sim\pm 0.2$ THz. Based on our observations, we believe this phonon-mediated process occurs between two different QDs, and the coupling between the QDs is enhanced by the presence of the cavity. Indeed, our results indicate that without a cavity spectrally close to one of the QDs, this process does not occur.

4. Cavity QED with a quantum dot coupled to a photonic molecule

Solid-state cavity QED systems consisting of a single quantum dot (QD) coupled to a photonic crystal cavity are of considerable interest to the quantum optics community for the generation of nonclassical states of light [3,22], for their application to all-optical [23,24] and electro-optical switching [25], and due to unusual effects like the off-resonant dot-cavity interaction due to electron-phonon coupling [10]. However, all of the cQED effects previously demonstrated in this system involve a single cavity. Although numerous theoretical proposals employing multiple cavities coupled to single quantum emitters exist in the cQED and circuit-QED literature [26–29] experimental development in this direction is rather limited. Most of these proposals, for example, observing the quantum phase transition of light, require a nonlinearity in each cavity, which is a formidable task with current technology. However, several proposals involving a single QD coupled to multiple cavities predict novel quantum phenomena, for example, the generation of bound photon-atom states [30] or sub-Poissonian light generation in a pair of coupled cavities or in a photonic molecule containing a single QD [31, 32]. This photonic molecule, coupled to a single QD, forms the first step toward building an integrated cavity network with coupled QDs.

We have demonstrated the effects of cavity quantum electrodynamics for a quantum dot coupled to a photonic molecule consisting of a pair of coupled photonic crystal cavities. In order to investigate the strong coupling between a single QD and the photonic molecule in PL, we used a photonic molecule consisting of cavities separated by four holes along the 60° angle. In practice it is not trivial to tune the QD over such a long wavelength range as required by the observed separation of the two cavity peaks. Hence, we use two different tuning techniques: we tune the cavity modes by depositing nitrogen on the cavity [33], and then tune the QD resonance across the cavity resonance by changing the temperature of the system. As shown in Fig. 4.1, we observe clear anticrossings between the QD and two supermodes formed in the photonic molecule, signifying achievement of the strong coupling regime. In general, the exact coupling strength between two cavities in a photonic molecule is difficult to calculate, as the observed separation between the two modes has contributions both from the cavity coupling strength as well as from the mismatch between the two cavities due to fabrication imperfections. However, by monitoring the interaction between a single QD and the photonic molecule we can exactly calculate the coupling strength between the cavities and separate the contribution of the bare detuning due to cavity mismatch. In fact, without any coupling between two cavities, one cannot have strong coupling of the QD with both of the observed modes. Hence, the observed anticrossing of the QD with both modes clearly indicates coupling between the cavities.

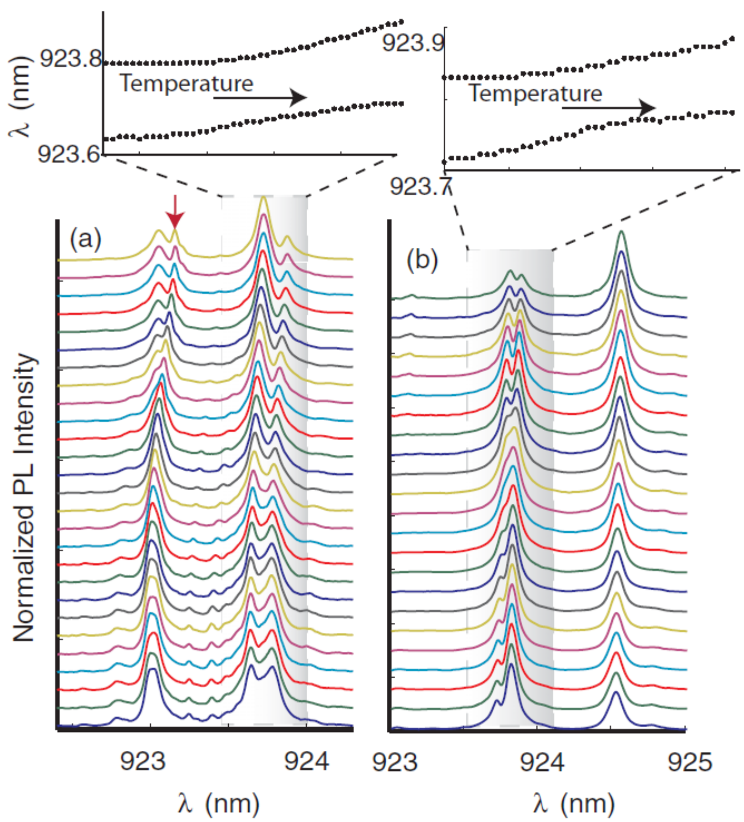

Figure 4.1 Normalized PL intensity plotted when we tune the QD across the cavity resonance by temperature: (a) before nitrogen deposition (i.e., the QD is temperature tuned across the longer wavelength resonance) and (b) after nitrogen deposition (which red-shifts the cavity resonances and allows us to temperature tune the QD across the shorter wavelength resonance). Clear anticrossings between the QD and the cavity are observed for both supermodes. In both cases, the temperature is increased from bottom to top (the plots are vertically offset for clarity). In the inset the resonances of the two anticrossing peaks (as extracted from curve fitting) are plotted. Clear anticrossing is observed in both cases.

We then perform curve fitting for the PL spectra when the QD is resonant to the cavity super-modes and estimate the system parameters [Figs. 4.2(a) and 4.2(b)]. Using the extracted values, we can numerically simulate the performance of such a QD-photonic molecule for generation of sub-Poissonian light using the quantum optical master equation approach [34]. The numerically simulated empty-cavity transmission and $g^2(0)$ of the transmitted light is shown in Figs. 4.2(c) and 4.2(d). From these simulated data, we observe that with our system parameters we should be able to achieve strongly sub-Poissonian light with $g^2(0) \sim 0.03$. Unfortunately, in practice it is very difficult to drive only one cavity mode without affecting the other mode due to the spatial proximity of two cavities. This individual addressability is critical for good performance of the system [32] and to retain such a capability in a photonic molecule the cavities should be coupled via a waveguide [35].

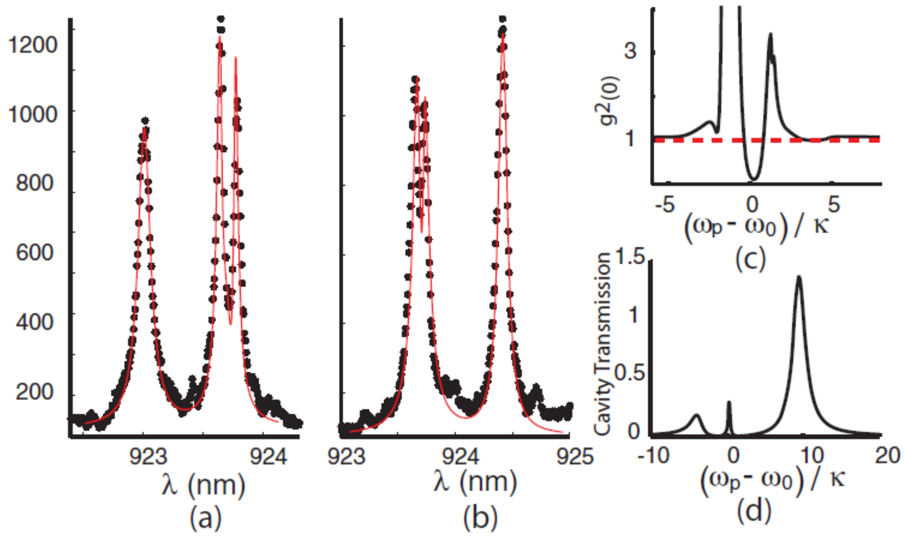

Figure 4.2 QD-photonic molecule spectrum: (a) when the QD is resonant with the longer-wavelength super-mode and (b) when the QD is resonant with the shorter-wavelength supermode. From the fit we extract the system parameters. Numerically simulated (c) second-order autocorrelation $g^2(0)$ and (d) transmission from the empty cavity, as a function of laser frequency, with the experimental system parameters that were extracted from the fits.

Finally, as a further demonstration of cQED effects in this system, we have demonstrated off-resonant interaction between the coupled cavities and the QD, similar to the observations in a single linear three-hole defect cavity [36] and a nanobeam cavity [37].

5. The effect of photo-generated carriers on the spectral diffusion of a quantum dot coupled to a photonic crystal cavity

We experimentally observed the effect of photogenerated carriers on the spectral diffusion of a quantum dot (QD) coupled to a photonic crystal (PC) cavity [38]. In this system, spectral diffusion arises in part from charge fluctuations on the etched surfaces of the PC. We find that these fluctuations may be suppressed by photogenerated carriers, leading to a reduction of the measured QD linewidth by a factor of ~2 compared to the case where the photogenerated carriers are not present. This result demonstrates a possible means of countering the effects of spectral diffusion in QD-PC cavity systems and thus may be useful for quantum information applications where narrow QD linewidths are desired.

We measure the QD linewidth by measuring the off-resonant cavity emission, while scanning the laser across the QD. We find a rather broad QD linewidth, in comparison to QD linewidths measured by resonant QD spectroscopies. A strong narrowing of the QD linewidth is observed when a little above-band laser is present (see Fig. 5.1). The new QD linewidth is of similar order of magnitude of the QD linewidths measured before. The broadening of the QD is most likely caused by the spectral diffusion due to random charging and uncharging of the states present at the etched surfaces. However, in presence of the AB laser charges are created. These charges can satisfy the states at the etched surfaces, and thus reduces the random charging and discharging, which in turn reduces the spectral diffusion.

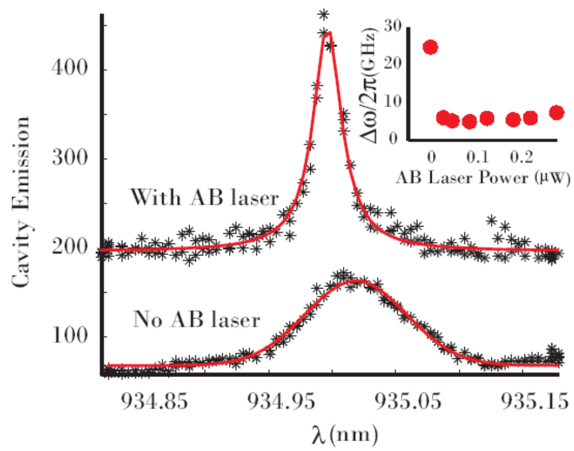

Figure 5.1: Effect of the above-band (AB) laser on the QD spectrum as measured though off-resonant cavity emission. In the absence of the AB laser, we observe a broad QD linewidth. However, in the presence of this laser, a significant linewidth narrowing is observed. The increased background with the AB laser on is caused by the PL generated by the AB laser. The inset shows the QD linewidth measured as a function of the AB laser power.

References

[1] A. Majumdar, D. Englund, M. Bajcsy, and J. Vučković, Phys. Rev. A 85, 033802 (2012).

[2] A. Majumdar, M. Bajcsy, and J. Vučković, Phys. Rev. A 85, 041801(R) (2012).

[3] A. Faraon, I. Fushman, D. Englund, N. Stoltz, P. Petroff, and J. Vučković, Nat. Phys. 4, 859 (2008).

[4] A. Kubanek *et al.*, Phys. Rev. Lett. **101**, 203602 (2008).

[5] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atature, S. Gulde, S. Falt, E. L. Hu, and A. Imamoğlu, Nature (London) 445, 896 (2007).

[6] D. Press, S. Götzinger, S. Reitzenstein, C. Hofmann, A. Löffler, M. Kamp, A. Forchel, and Y. Yamamoto, Phys. Rev. Lett. 98, 117402 (2007).

[7] M. Kaniber, A. Laucht, A. Neumann, J. M. Villas-Boas, M. Bichler, M.-C. Amann, and J. J. Finley, Phys. Rev. B 77, 161303(R) (2008).

[8] D. Dalacu, K. Mnaymneh, V. Sazonova, P. J. Poole, G. C. Aers, J. Lapointe, R. Cheriton, A. J. SpringThorpe, and R. Williams, Phys. Rev. B 82, 033301 (2010).

[9] A. Laucht, N. Hauke, A. Neumann, T. Günthner, F. Hofbauer, A. Mohtashami, K. Müller, G. Böhm, M. Bichler, M.-C. Amann et al., J. Appl. Phys. 109, 102404 (2011).

[10] D. Englund, A. Majumdar, A. Faraon, M. Toishi, N. Stoltz, P. Petroff, and J. Vučković, Phys. Rev. Lett. 104, 073904 (2010).

[11] S. Ates, S. M. Ulrich, A. Ulhaq, S. Reitzenstein, A. Löffler, S. Höfling, A. Forchel, and P. Michler, Nat. Photonics 3, 724 (2009).

[12] M. Winger, T. Volz, G. Tarel, S. Portolan, A. Badolato, K. J. Hennessy, E. L. Hu, A. Beveratos, J. Finley, V. Savona et al., Phys. Rev. Lett. 103, 207403 (2009).

[13] N. Chauvin, C. Zinoni, M. Francardi, A. Gerardino, L. Balet, B. Alloing, L. H. Li, and A. Fiore, Phys. Rev. B 80, 241306(R) (2009).

[14] A. Laucht, J. M. Villas-Bôas, S. Stobbe, N. Hauke, F. Hofbauer, G. Böhm, P. Lodahl, M.-C. Amann, M. Kaniber, and J. J. Finley, Phys. Rev. B 82, 075305 (2010).

[15] E. del Valle, F. P. Laussy, F. Troiani, and C. Tejedor, Phys. Rev. B 76, 235317 (2007).

[16] F. P. Laussy, A. Laucht, E. del Valle, J. J. Finley, and J. M. Villas-Bôas, Phys. Rev. B 84, 195313 (2011).

[17] A. N. Poddubny, M. M. Glazov, and N. S. Averkiev, Phys. Rev. B 82, 205330 (2010).

[18] P. C. Cárdenas, N. Quesada, H. Vinck-Posada, and B. A. Rodríguez, J. Phys.: Condens. Matter 23, 265304 (2011).

[19] K. J. Xu and C. Piermarocchi, Phys. Rev. B 84, 115316 (2011).

[20] E. Gallardo, L. J. Martinez, A. K. Nowak, D. Sarkar, H. P. van der Meulen, J. M. Calleja, C. Tejedor, I. Prieto, D. Granados, A. G. Taboada et al., Phys. Rev. B 81, 193301 (2010).

[21] E. B. Flagg, J. W. Robertson, S. Founta, W. Ma, M. Xiao, G. J. Salamo, and C.-K. Shih, Phys. Rev. Lett. 102, 097402 (2009).

[22] A. Majumdar, M. Bajcsy, and J. Vučković, Phys. Rev. A 85, 041801(R) (2012).

[23] D. Englund, A. Majumdar, M. Bajcsy, A. Faraon, P. Petroff, and J. Vučković, Phys. Rev. Lett. 108, 093604 (2012).

[24] R. Bose, D. Sridharan, H. Kim, G. S. Solomon, and E.Waks, Phys. Rev. Lett. 108, 227402 (2012).

[25] A. Faraon, A. Majumdar, H. Kim, P. Petroff, and J. Vučković, Phys. Rev. Lett. 104, 047402 (2010).

[26] M. J. Hartmann, F. G. S. L. Brandao, and M. B. Plenio, Nat. Phys. 2, 849 (2006).

[27] A. D. Greentree, C. Tahan, J. H. Cole, and L. C. L. Hollenberg, Nat. Phys. 2, 856 (2006).

[28] A. A. Houck, H. E. Treci, and J. Koch, Nat. Phys. 8, 292 (2012).

[29] I. Carusotto, D. Gerace, H. E. Tureci, S. De Liberato, C. Ciuti, and A. Imamoğlu, Phys. Rev. Lett. 103, 033601 (2009).

[30] P. Longo, P. Schmitteckert, and K. Busch, Phys. Rev. Lett. 104, 023602 (2010).

[31] T. C. H. Liew and V. Savona, Phys. Rev. Lett. 104, 183601 (2010).

[32] M. Bamba, A. Imamoğlu, I. Carusotto, and C. Ciuti, Phys. Rev. A 83, 021802 (2011).

[33] S. Mosor, J. Hendrickson, B. C. Richards, J. Sweet, G. Khitrova, H. M. Gibbs, T. Yoshie, A. Scherer, O. B. Shchekin, and D. G. Deppe, Appl. Phys. Lett. 87, 141105 (2005).

[34] A. Majumdar, E. D. Kim, Y. Gong, M. Bajcsy, and J. Vučković, Phys. Rev. B 84, 085309 (2011).

[35] Y. Sato, Y. Tanaka, J. Upham, Y. Takahashi, T. Asano, and S. Noda, Nat. Photon. 6, 5661 (2012).

[36] A. Majumdar, A. Faraon, E. D. Kim, D. Englund, H. Kim, P. Petroff, and J. Vučković, Phys. Rev. B 82, 045306 (2010).

[37] A. Rundquist, A. Majumdar, and J. Vučković, Appl. Phys. Lett. 99, 251907 (2011).

[38] A. Majumdar, E. D. Kim, and J. Vučković, Physical Review B, 195304 (2011).